Tropical Cyclone Predictability

PI Prof Lance M. Leslie
School of Mathematics, University of New South Wales
Sydney 2052, Australia
Ph: 61-2-93857071, Fax: 61-2-93857123
E-mail: L.Leslie@unsw.edu.au

Co-PI Dr. Greg J. Holland
Bureau of Meteorology Research Centre, Melbourne, Australia

Award Number: N00014-94-1-0556
http://www.vislab.usyd.edu.au/staff/wwang/\
http://www.bom.gov.au/bmrc then Mesoscale Meteorology

LONG-TERM GOALS

There are three major long-term goals of this program:

- To define, and attempt to approach in practice, the limits of errors in tropical cyclone forecast track predictability;
- To develop techniques for predicting tropical cyclone intensity and intensity change;
- To estimate the predictability of tropical cyclone intensity forecasting.

OBJECTIVES

The scientific objectives of the effort are to apply several techniques developed within the program, including Monte Carlo ensemble approaches, techniques adapted from non-linear systems analysis and optimal combinations of forecasting approaches to estimating the intrinsic limits to predictability for (i) tropical cyclone mean forecast position errors in the first instance, and (ii) to tropical cyclone intensity in the second part of the program. These intrinsic limits exist because the equations governing the behavior of all atmospheric systems including tropical cyclones are deterministically chaotic. Thus errors in the initial conditions and model formulation lead to error growth that eventually reduces the skill of the forecasts to zero. The intrinsic limits are to be compared with the results being obtained in practice and the size of the disparity represents the gains in predictive skill that are still achievable. It is of fundamental importance to have some idea of how large the gap is between that being obtained and the ultimately achievable in order to justify the continued allocation of resources to the various problems. A substantial part of the research objectives is developing a data assimilation and prediction scheme that can produce improved forecasts of tropical cyclone intensity.

APPROACH

The approach is distinctive for each of the three goals.

The methodology employed for the first goal has been explained fully in a series of articles (Abbey et al., 1995,1997,1999; Leslie et al., 1998) and involves the use of two quite distinct techniques that yield almost identical answers thereby adding confidence to the findings. The first goal, as mentioned above, is to provide estimates of the lowest possible mean forecast track errors out to 72 hours and to determine how closely current forecast systems are to these limits. The practical limits

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Tropical Cyclone Predictability**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of New South Wales,School of Mathematics,Sydney 2052, Australia,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

naturally are changing (improving) steadily as the sustained effort in tropical cyclone track forecast continues at centers around the world. Using the PI's model as representative of these models the approach has been to apply a modified Monte Carlo technique to the archived data sets of various operational NWP centers around the world (Australian Bureau of Meteorology, UKMO and NCEP). Ensembles of forecasts are generated by perturbing the initial conditions and the fields at 12 hourly intervals out to 72 hours after re-setting the tropical cyclone positions back to their best track locations every 12 hours. This approach has proven to be very robust and almost insensitive to the time interval between re-setting the tropical cyclone positions to their best track locations. The alternative is to use a non-linear systems approach to the archived best track data sets in the manner described by Fraedrich and Leslie (1988). Here, the spread of initially close pieces of tropical cyclone trajectories is calculated over a 72 hour period for all available data sets.

The second goal, which is well underway, is to obtain much more realistic tropical cyclone intensification rates and patterns from numerical models. Numerical models to date have been producing steadily improving forecasts of tropical cyclone tracks but are grossly mis-forecasting the intensity of the storms. Some successes have been achieved using bogussed vortices and other initialization procedures but this PI preferred to work in the classical manner of improving data coverage and quality, data assimilation procedures, model formulation and model resolution. A breakthrough came earlier this year when, as described in the results section, the four-dimensional assimilation of high spatio-temporal frequency satellite derived data of various types, together with very high resolution modelling (5 km) and improved treatment of moist processes in the model produced very good forecasts of tropical cyclone intensification.

The third goal, which will be a focus of the second half of the project, will be to examine the predictability of tropical cyclone intensification. This will be a difficult task but one for which there simply are no shortcuts if believable limits are to be produced. The approach has not finally been settled upon as it is part of the second year of this current proposal. However it is most likely to be some variant of the first approach with the application of various techniques for obtaining estimates of both the inherent and practical limits of predictability for tropical cyclone intensity prediction. These limits will then be compared for the various tropical cyclone basins and will again provide information about how close current operational models are to the limits of predictability.

WORK COMPLETED

Two tasks have commenced in the first year of the current proposal. One has been completed and a second is well underway. The first goal of comparing the difference between the mean absolute forecast track errors for tropical cyclones obtained in practice with estimates of what could be achieved in principle has been completed The findings are summarized below and in the forthcoming 23rd Conference on Hurricanes and topical Meteorology at which the work will be presented. The second goal of improving forecasts of tropical cyclone intensity and intensity change has yielded very promising results and also will be presented at the 23rd Conference as well as other meetings and has been submitted to several peer-reviewed journals.

RESULTS

The four main sets of results are presented in turn, below.

The first was to determine how close current NWP model forecasts are to the best estimate of the limit of predictability for tropical cyclones as systems governed by a set of deterministically chaotic equations. The chaotic nature of the systems and the governing equations results from the non-linearity of the system together with the multifarious feedback processes that take place in such complex systems. Table 1 summarizes the final set of findings from three tropical cyclone basins (Atlantic, NW Pacific and Australian region) using four years of best track archived data for the period 1994-1997. The first row is the estimate of the lower limit of predictability obtained using non-linear systems analysis applied to the data and is called Inherent 1. The second row is the corresponding estimate obtained using the Monte Carlo generated ensemble NWP procedure described in the approach section. It is referred to as Inherent 2. The interesting feature is how close the estimates are from these two very different approaches to estimating predictability.

The potential for approaching these predictability limits was tested by application of linear combination techniques. It can be shown that in theory a linear combination of several forecasts will always yield a superior forecast when averaged over a large number of forecasts. The appropriate covariances have to be calculated and this is a very time consuming effort. However, the rewards came in the form of the results in row 3 of Table 1, which indicated a significant reduction in topical cyclone track forecast errors when the forecasts from the UNSW, UKMO and NCEP model were combined. It is noted that this approach, referred to as Inherent 3 should be applied rigorously and simple averages might yield short term gains but have no genuine mathematical basis. It is planned to add the NRL model NOGAPS to the list of models employed in the combination sometime next year.

The major finding is that there is still a large gap of somewhere between 35 to 50% in what is being achieved at present and what is possible.

Table 1: Inherent error limits (km) for the three methodologies out to 72 hours. These are to be compared with the errors currently being obtained in practice as shown on the bottom row.

	0 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Inherent 1	0	39	79	96	135	169	213
Inherent 2	37	53	85	102	141	177	224
Inherent 3	27	45	66	92	123	142	191
Practical	52	84	121	157	219	264	322

The results obtained thus far for the second goal have arguably been the most exciting part of this current proposal. Currently, tropical cyclone intensity forecasts are quite poor. Some success has been obtained by other researchers who used bogus techniques to provide the initial location, intensity, size, asymmetry and speed and direction of movement of the tropical cyclone vortex. However we have shown in earlier work that there are major problems with the use of bogus techniques. By the use of a long period of numerical experiments using a range of resolutions, data assimilation techniques and model formulations and resolutions it was finally found (Leslie and LeMarshall, 1998a,b) that realistic intensification of tropical cyclones could be obtained simply by: 1. using the standard methods of high temporal and spatial resolution data during assimilation and, 2.

using an effective initialization procedure based on the model equations and the use of very high resolution in the forecast model. One example of the ten forecasts so far carried out is shown below in Figure 1 for Australian tropical cyclone Olivia.

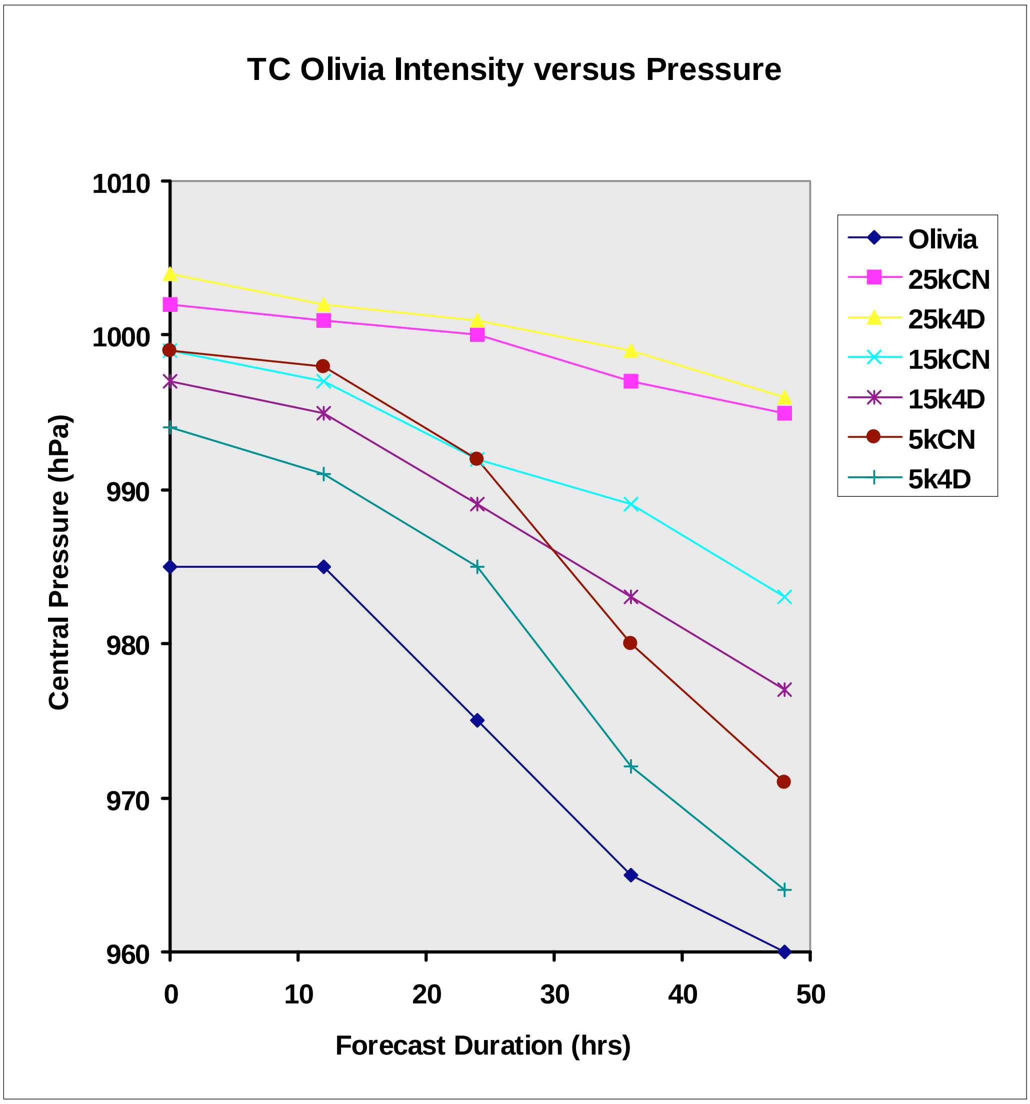

Figure 1 Forecasts of central pressure for tropical cyclone Olivia over a 48 period in which the tropical cyclone intensified by over 30 hPa. The model resolution is indicated by numbers and four "control" (CN) runs indicated the effects of varying model resolution without satellite data. Intensification varied from almost zero to about 20 hPa in the case of the 5 km resolution model.

By contrast, when the control model was rerun with the high resolution satellite derived data (4D) only the coarsest resolution model (25 km) did not produce significant intensification.

As seen clearly in the figure, forecasts with low resolution in either the data or the model did not adequately represent the best track estimates of the central pressure of tropical cyclone Olivia. Realistic intensification rates were obtained from forecasts that employed high resolution in both the data and the model. These results have been achieved without bogussing or special initialization procedures.

IMPACT/APPLICATIONS

There are a number of significant areas of impact/applications. The first is the demonstration that tropical cyclone track forecast errors are still large compared to the ultimate predictability limit. Hopefully this knowledge will act as a major encouragement for continued progress in tropical cyclone track forecasting. A second impact is the demonstration of the primary role of data and model resolution in achieving realistic forecasts. This finding is independent of but consistent with work being carried out by the modelling effort of another PI, Dr Greg Holland.

TRANSITIONS

There will be a meeting with scientists from NRL Monterey in January 1999 year to discuss possible applications of this work to the operational program at NRL Monterey. Some past work already has been used at Monterey but this will new work has potential for transition in the tropical cyclone forecasting area and the data assimilation program more generally.

RELATED PROJECTS

There are some strong links with the ONR funded program of Dr Greg Holland in assessing the impact of the Aerosonde data on tropical cyclone track and intensity prediction and with another PI, Dr JCL Chan on tropical cyclone predictability using ensemble techniques.

REFERENCES

Abbey, R.F. Jr., L.M. Leslie and G.J. Holland, 1995: Tropical cyclone track predictability: Parts I, II and III. *Proc. 21st Conference on Hurricanes and Tropical Meteorology*, Miami, American Meteorology Society, pp 160.

Abbey, R.F. Jr., L.M. Leslie and G.J. Holland, 1997: Tropical cyclone track predictability: PartII *Proc. 22nd Conference on Hurricanes and Tropical Meteorology*, Fort Collins, American Meteorology Society, 201-204.

Abbey, R.F. Jr., L.M. Leslie and G.J. Holland, 1999: Tropical cyclone track predictability: Parts I, II and III. *Proc. 23rd Conferences on Hurricanes and Tropical Meteorology*, American Meteorology Society, Dallas, (to appear).

Fraedrich, K and LM Leslie, 1988: Estimates of tropical cyclone track predictability. I: Tropical cyclones in the Australian region. *Quart. J. Roy. Meteor. Soc.*, **115**, 79-92.

Leslie, LM and JF LeMarshall, 1998a: Prediction of Atlantic hurricanes in the 1995 season. *Mon. Wea. Rev.*, 1248-1257.

Leslie, LM and JF LeMarshall, 1998b: Tropical cyclone intensity prediction using very high resolution satellite data. *Mon. Wea. Rev.*, (submitted)

Leslie, LM, Abbey, RF and Holland, GJ (1998): Tropical cyclone predictability. *Meteorology and Atmospheric Physics*, **65**, 223-232.

PUBLICATIONS

Leslie, LM and Skinner, TCL (1998) Numerical prediction of the summertime ridge-trough system over tropical northeastern Australia. Weather and Forecasting, 12, (Accepted)

Leslie, LM and Speer, MS (1998) Comments on short range ensemble forecasting of explosive Australian east coast cyclogenesis, Weather and Forecasting, 12, (In press, December issue)

Tan, KA and Leslie, LM (1998) A high performance workstation cluster for numerical weather prediction, pp 1111-1119. In High Performance Computing : Technology Driver for Academia, Business and Industry. Volumes 1 and 2. Eds. KY Lam, BC Khoo and K Kumar. Published by Institute of High Performance Computing, 89 Science Park Drive, Singapore. 1439 pp. ISBN : 981-04-0634-7.

LeMarshall, JF and Leslie, LM (1998) Recent developments in the continous assimilation of satellite wind data for tropical cyclone track forecasting. Advances in Space Research, 20, (Accepted).

Surgi, N and Leslie, LM (Editors) (1998) Tropical Cyclones, Meteorology and Atmospheric Physics, 65, 139-245

Buckley, BW and Leslie, LM (1998) High resolution numerical of Tropical Cyclone Drena undergoing extra-tropical transition, Meteorology and Atmospheric Physics, 65, 207-222.

Leslie, LM, Abbey, RF and Holland, GJ (1998) Tropical cyclone predictability, Meteorology and Atmospheric Physics, 65, 223-232

Tan, KA and Leslie, LM (1998) Development of a non-hydrostatic model for atmospheric modelling. In Computational Techniques and Applications: CTAC97, Editors: Noye, BJ, Teubner, MD and Gill, AW, World Scientific Press, Singapore, pp 679-686

Leslie, LM, LeMarshall, JF and Morison, PR (1998) Prediction of Atlantic hurricanes in the 1995 season, Monthly Weather Review, 125, 1248-1257

LeMarshall, JF and Leslie, LM (1998) Tropical cyclone track prediction using very high resolution satellite data. Aust. Meteor. Mag., 47, 261-266.

Leslie, LM and Fraedrich, K (1997) A new general circulation model: Formulation and preliminary results, Climate Dynamics, 13, pp. 35 - 43.

Bennett, AF, Chua, BS and Leslie, LM (1997) Generalised inversion of a global numerical weather prediction model: Part II: Analysis and implementation, Meteorology and Atmospheric Physics, 62, pp 129-140

Leslie, LM and Dietachmayer, GS (1997) Comparing schemes for integrating the Euler equations, Monthly Weather Review, 125, 1687-1791

LeMarshall, JF, Leslie, LM and Spinoso, C (1997) The assimilation of satellite wind data for tropical cyclone track forecasting. Chapter in Data assimilation in Meteorology and Oceanography, Eds. M. Ghil, K. Ide, A. Bennett, P.Courtier, M. Kimoto, M. Nagata, M. Saiki, N. Sato. Universal Academy Press Inc., Tokyo., 383-393

Leslie, LM and Purser, RJ (1997) A new class of generalised Lorenz numerical integration schemes, Monthly Weather Review, 125, 1261- 1276.

Leslie, LM and Purser, RJ (1997) A new semi - Lagrangian semi - implicit NWP model for operations and research: Formulation and performance in single and multi - processor computing environments, Atmosphere - Ocean, Special Andre Robert memorial Issue, Canadian Meteorological and Oceanographic Society/NRC Research Press, (Eds. C.A. Lin, R. Laprise and H. Ritchie), pp 75-101.

Leslie, LM and LeMarshall, JL (1997) The generation and assimilation of cloud drift winds in numerical weather prediction, Journal of the Meteorological Society of Japan, 75, 273-285.

IN-HOUSE/OUT-OF-HOUSE RATIOS

10/90